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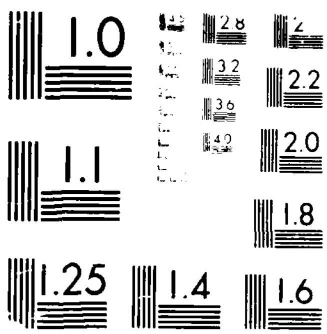

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REPORT SD-TR-88-22

Nickel Hydrogen Low Earth Orbit Life Testing

AD-A191 946

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

A program to demonstrate the long-term reliability of nickel hydrogen (NiH_2) cells in low earth orbit (LEO) and support use in mid-altitude orbit (MAO) has been initiated. Both 3.5 and 4.5 in. diameter NiH_2 cells are included in the test plan. Cells from all U.S. vendors are to be tested. The tests will be performed at -5 and 10°C at 40 and 60% depth of discharge (DOD) for LEO orbit and 10°C and 80% DOD for MAO orbit simulations. The goals of the testing are 20,000 cycles at 60% DOD and 30,000 cycles at 40% DOD. Cells are presently undergoing acceptance and characterization testing at Naval Weapons Support Center (NWSC), Crane, Indiana. Funding has been provided by the Air Force Space Technology Center (AFSTC) and two AF System Program Offices (SPO's) to initiate the testing, but additional funding must be acquired to complete the purchase of cells and to assure completion of the testing.

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CONTENTS

TABLES

FIGURE

I. INTRODUCTION

The use of nickel hydrogen (NiH_2) batteries in high earth orbit (HEO) applications is well established. Sufficient test data are available to make estimates of the actual reliabilities for both the communications satellite (COMSAT) and the Air Force/Hughes designed cells. However, the application of properly designed NiH_2 cells to low earth orbit (LEO) has not been demonstrated. A program has been initiated by the USAF Space Technology Center (STC) to develop the necessary data base to support use of NiH_2 batteries in LEO at levels that would offer significant improvements in life and depth of discharge (DOD) over present state-of-the-art nickel cadmium (NiCd) batteries. The program is to be performed at Naval Weapons Support Center (NWSC), Crane, Indiana, using new test control facilities. The plans, requirements, and status of the test program are presented.

II. BACKGROUND

In Spring 1984, a survey of life testing status and results for NiH_2 cells was performed.[1] Data were found to either be available or to be made available within the next 2 to 3 years to demonstrate reliability and confidence in the use of NiH_2 batteries in high earth orbits (HEO's) requiring up to 3000 cycles at maximum DOD of up to 80%. Calendar life on orbit in excess of 10 years was anticipated. It was suggested that optimum performance would be achieved when the temperature of operation was at less than 15°C, and the amount of overcharge should be minimized while maintaining an adequate state of charge.

The data available to support use of NiH_2 batteries in LEO are deficient. The extant data base consists of mixtures of technologies and several generations of LEO cell designs. Cells have been tested under extreme conditions with less regard for the limitations of these cells than is normally applied to aerospace secondary cells. By the same token, testing of the most recently built cells under severe conditions (90 min cycle, 80% DOD, 1.4 C discharge, where C is the capacity of the cell, 0.8 C charge, 105% charge return ratio, 23 ± 4°C) has consistently given 10,000 cycles before failure (due to low voltage) occurred. This suggests that the cells have the capability to surpass the performance of present state-of-the-art NiCd cells in LEO applications. Presently, design variations among NiH_2 cells are beginning to stabilize, and future changes are expected to be incremental. Testing to establish reliability and performance appears to be practical at this time.

NiH_2 cells must significantly outperform NiCd cells or they would be disadvantageous to use because of their greater specific volume, present higher unit cost, and the risks inherent in any new design. This increase in

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[1] C.C. Badcock and M. J. Milden, "An Industry and Government Survey: Life Testing of Nickel Hydrogen Cells," Proceedings of the 1984 GSFC Battery Workshop, NASA Conf. Pub. 2382 (1985), p. 583.

performance can be in life and/or usable energy density. Present NiCd batteries used under near-optimum conditions offer 14-18,000 cycles at 20-25% DOD and 25-30,000 cycles at 7-14% DOD with high reliability and confidence depending on the specific load profile, power system requirements, and environment. NiH_2 cells must demonstrate significant increases over these levels if they are to be the next generation of LEO batteries. This life test will demonstrate the performance capabilities of state-of-the-art NiH_2 cells in LEO and will provide a data base, when combined with other relevant life test data and with program specific testing, that will permit an estimate of reliability at an appropriate confidence level. State-of-the-art, individual pressure vessel-type cells of 3.5 and 4.5 in. diameter are to be tested.

A. OBJECTIVES

The test will be a predominantly LEO regime (90 min orbit with 30 min of eclipse and 60 min of sun) with some test packs tested in mid-altitude orbit (MAO)-to-HEO conditions (400 to 500 cycles per year with a 4 to 12 hour orbit) if funding and schedule permit. The NiH_2 cell life test plan has the following objectives:

1. Demonstrate NiH_2 performance in LEO applications and support use in MAO at levels superior to current NiCd capabilities.
2. Develop a statistically significant NiH_2 battery cell data base.
3. Disseminate the test data and results in a timely fashion.
4. Demonstrate NiH_2 cell performance in pulse applications.
5. Demonstrate that the Manufacturing Technology Program (MANTECH) cells are capable of performing in HEO as well as LEO.

B. STATISTICAL REQUIREMENTS

The statistical requirements for a test must be based on the largest homogeneous unit: single type of cell, same vendor, same test conditions. Analysis after testing has progressed may justify the combination of several of these units to increase the reliability and confidence level for a particular application. Generally tests performed under more severe conditions can support reliability assessments for applications at less severe stress levels.

The two-parameter Weibull function (zero failure rate at the start of the test is assumed) will be used to estimate reliability. The expression for the reliability after integration of the probability density function is

$$R(t) = \exp[-(t/\mu)\beta] \quad (1)$$

where β is the shape of the failure distribution parameter, μ is the scale parameter associated with the rate of failure, and t is the test time.[2] This is a general function that reduces to an exponential distribution function ($\beta = 1$) or closely approximates a normal distribution function ($\beta = 3.313$). The use of the function for evaluating NiCd test data has been demonstrated.[3] When no failures occur in a test that has run for time t, the success-run theorem (Bayes' Formula)

$$R = (1 - c)^{1/(n+1)} \quad (2)$$

can give the relationship between confidence level c, the reliability at that confidence level R, and the sample size n.[2] Table 1 shows the relationship between sample size, test time, reliability, and confidence level for an assumed normal distribution ($\beta = 3.313$). Ten cell packs are chosen as the test unit because of the reliability and confidence levels attainable and because this sample size permits evaluation of the failure distribution function.

C. REPORTING

Reports will be issued when significant milestones are reached and at regular periods. Each major milestone, e.g., completion of acceptance testing, will result in a brief report. The progress of the test will be

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[2] C. Lipson and N. J. Sheth, Statistical Design and Analysis of Engineering Experiments, McGraw-Hill, New York (1973).

[3] J. H. Matsumoto, G. Collins, and W. C. Hwang, "Applicability of Accelerated Test Data," Proceedings of the 19th Intersociety Energy Conversion Engineering Conference, Vol. 1, 303 (1984).

Table 1. Test Time, Reliability, and Confidence Level for a 5 Year Application as a Function of the Sample Size

Sample Size Without Failure	Test Time (R=90%, c=69%)	Reliability (c=69%, t=5 yr)	Confidence Level (R=90%, t=5 yr)
1	8.36 yr	56.0%	19.0%
2	7.40	68.0	27.1
3	6.78	74.9	34.4
5	6.00	82.4	46.9
6	5.73	84.7	52.2
7	5.50	86.5	57.0
8	5.31	87.9	61.3
9	5.15	89.1	65.1
10	5.00	90.0	68.7
15	4.46	93.0	81.5
20	4.12	94.6	89.1

reported in an Annual of Cycle Life Testing and will, in addition, be summarized at least once a year and presented in an appropriate forum. The detailed data will remain available for access by qualified organizations.

D. COORDINATION WITH OTHER TESTING

In a separate, program-oriented test, Martin-Marietta Aerospace in Denver is performing similar life testing. Their test matrix has been coordinated with this matrix to assure proper distribution and adequate data at the key points, that is, at the center 10°C test area. They are planning to test at 20°C, which accounts for that condition missing from this matrix. Any other testing data that become available and that are relevant will be incorporated into the growing data base.

E. TEST ARTICLES

It is the intent to test cells from all viable vendors in sufficient numbers to provide a comparison and to establish a statistically significant data base with a sufficiently high confidence level. A minimum of 155 3.5 in. diameter and 45 4.5 in. diameter cells are included in the test plan. Additional cells will be added as the need is demonstrated. Insofar as schedule and funding permits, approximately equal numbers of cells from the four U.S. vendors [General Electric Battery Business Department (GEBBD), Eagle Picher, Yardney, and Hughes Aircraft Corporation (HAC)] are to be tested. The initial test articles will be 3.5 in. diameter cells drawn from purchase orders previously placed with Yardney, Eagle Picher, and GEBBD by Air Force Wright Aeronautical Laboratories (AFWAL)/POOC and AFWAL/ML. It is hoped that part of the complement of 4.5 in. diameter cells will be drawn from orders already placed [common pressure vessel (CPV) program] by AFWAL/POOC.

In the future, cells will be purchased to a Specification of Nickel Hydrogen Cells that defines required performance in terms of voltage, capacity, weight, dimensions, and life. Presently used specifications will be covered by this specification because present versions specify additional details that are to be in the manufacturing control document (MCD) or present test requirements are less severe. Each vendor's product will be procured to a designated part number with the details of construction contained in an associated, approved MCD. Stability, performance, and conformance to specification will be demonstrated at each vendor's facility. Formal acceptance testing is to be performed at the testing location (NWSC, Crane, Indiana).

All cells will be in flight configuration (no special test units) and of flight quality. The cells are to be hermetically sealed. Pressure monitoring will be by externally mounted strain gauges only.

III. TEST OUTLINE

The test consists of acceptance and characterization testing, life testing, and failure and end-of-test analyses.

A. PRELIFE TESTING

Acceptance testing will be conducted at the life test site. Tests include standard capacities at -5, 10, and 20°C using rates appropriate to LEO applications (a rate of C is proposed because this approximates the conditions of the test), overcharge stability and reference capacities, and charged stand loss determinations. The ampere-hour and watt-hour capacities of the cells will be reported to 1.20, 1.15, 1.10, 1.05, 1.00, and 0.5 V. These data will provide reference data for system applications.

A 20% sample of the cells of each type (at least two cells) and from each vendor shall be subject to random vibration testing at levels 6 dB higher than the highest level anticipated in any application. The cells that are vibrated will be distributed throughout the test packs to determine any effects of vibration.

Characterization tests will be performed to determine the required charge characteristics. A group of five cells of each type and from each vendor will be tested to determine charge efficiencies at selected rates and temperatures. Watt-hour and ampere-hour efficiencies will be determined at four charge rates, three discharge rates, and at four temperatures.

The cells are to be assembled into test packs which contain cells from only one vendor. Heat removal is by conduction through flanges attached to the cells onto thermally conductive plates. The flanges will be of a standard type similar to the units used on previous USAF/Hughes-type cells to provide for similar heat removal pathways and rates for all cells. Each pack will have at least one cell with a pressure transducer.

B. LIFE TESTING

The goals for these tests are to demonstrate at least 30,000 cycles at 40% DOD and at least 20,000 cycles at 60% DOD in LEO and at least 5000 cycles at 80% DOD in MAO or HEO. The 40% DOD level is greater than present NiCd cells can expect to achieve at 3 years planned life. A small number of cells (five from each vendor) will be tested at 25% DOD to provide correlation with present NiCd testing and life data bases. Cells could fail to reach a desired goal, e.g., 60% DOD and 5 years, and still perform significantly better than present state-of-the-art NiCd cells.

A second goal is to establish a minimum reliability of 90% with a confidence level of at least 80% at the cycle lives stated above. This goal requires one additional year of testing beyond the life goals stated, but assumes that none of the groups of ten cells can be statistically combined.

The DOD is defined as the percent of the measured capacity to 1.00 V of the lowest capacity cell in the test pack under the most appropriate conditions in acceptance testing. This number may be higher or lower than the rated capacity used during acceptance testing.

Failure is defined as a voltage of less than 0.50 V at the end of the prescribed discharge or a voltage greater than 1.75 V during any portion of the charge. Data for other end-of-useful-life criteria will be available. Upon being declared a failure, the cell will be removed from the test pack and subjected to a repeat of at least part of the acceptance test within 180 days of failure. The cell shall then be dispositioned for failure analysis.

Data (current, voltage, pressure, and temperature) will be recorded for each test pack with sufficient frequency to assure that extrapolation between data points can be performed with adequate accuracy to detect any short-term or long-term trends. These data will be available for plotting or display and for the computation of watt-hour and ampere-hour input and output as well as charge returns. Periodically, e.g., every 2000 cycles, a complete plot of a charge/discharge cycle will be generated for each cell in test for comparison to detect trends.

The distribution of cells, the DOD's, and the temperatures are shown in Table 2 for the completely funded test and for the minimum test necessary to meet the primary goals. The LEO test will use 90 min cycles with 30 min discharges.

The charge procedure will consist of a high rate charge to return the bulk of the charge removed and a lower rate to complete the charge. This prevents subjecting the cells to high rate overcharge. The planned charge control method is ampere-hour integration (recharge fraction control). This method is flexible and particularly easy to integrate into a digital control system. Control shall be accomplished by changing the charge returned under a fixed DOD until the following parameters are minimized:

1. The decrease in the end of discharge voltage.

2. The increase in the end of charge voltage (high rate and trickle).

3. The recharge fraction (both watt-hour and ampere-hour).

These parameters will be adjusted during the test as performance dictates.

Reconditioning will not be performed on the cells in LEO testing. MAO testing may require reconditioning to maintain adequate efficiency. No capacity discharges shall be performed.

The test is scheduled over a 7 year period as shown in Fig. 1. To maximize the information and provide the best statistics, the test should continue until the majority of the cells in each pack have failed.

C. SPECIAL TESTING

The general test plan will use continuous constant current discharges. However, the applications requiring pulsed high rate discharge within the envelope of the planned DOD's are sufficiently prevalent to make the correlation of such results with the general life test important. A small group of cells will be placed on life test in a pulsed discharge regime at maximum rates of approximately 5 C. The detailed test plan for this portion will conform to the overall test organization but will be prepared separately. Cells will be acceptance tested at the testing organization and sent to The Aerospace Corporation Battery Evaluation Laboratory for this testing.

Table 2. Planned NiH_2 Life Test Matrix

Orbit	DOD	Manu-facturer	3.5 in. Dia. Cells[1] Temperature[2] 10°C	3.5 in. Dia. Cells[1] Temperature[2] -5°C	4.5 in. Dia. Cells[1] Temperature[2] 10°C	Total Cells 3.5 in.	Total Cells 4.5 in.
LEO	25%	Yardney	5			5	
		EP[3]	5			5	
		GEBBD[4]	5			5	
		HAC[5]	5			5	
	40%	Yardney	10	10		20	
		EP	10		10	10	10
		GEBBD	10	10		20	
		HAC	10		10	10	10
	60%	Yardney	10		10	10	10
		EP	10	10		20	
		GEBBD	10		10	10	10
		HAC	10	10		20	
MAO	80%	Yardney	10 (5)		10 (0)	10 (5)	10 (0)
		EP	10 (0)		10 (0)	10 (0)	10 (0)
		GEBBD	10 (0)		10 (0)	10 (0)	10 (0)
		HAC	10 (0)		10 (0)	10 (0)	10 (0)
Special Tests:							
	2 or 3 - 3.5 in. cells and 1+ - 0 4.5 in. cell from each vendor				10	5	
Total Cells[6,7]					190 (155)	85 (45)	

[1]The complete test configuration is shown with the minimum credible test shown in parentheses where the two differ.

[2]The temperatures specified are to have tolerances of ±4°C.

[3]Eagle Picher.

[4]General Electric Battery Business Department.

[5]Hughes Aircraft Corporation.

[6]Strain gauge pressure monitors are required on at least 20% of the cells.

[7]An additional set-aside of one wet and one dry cell of each size from each manufacturer is recommended (not in above totals).

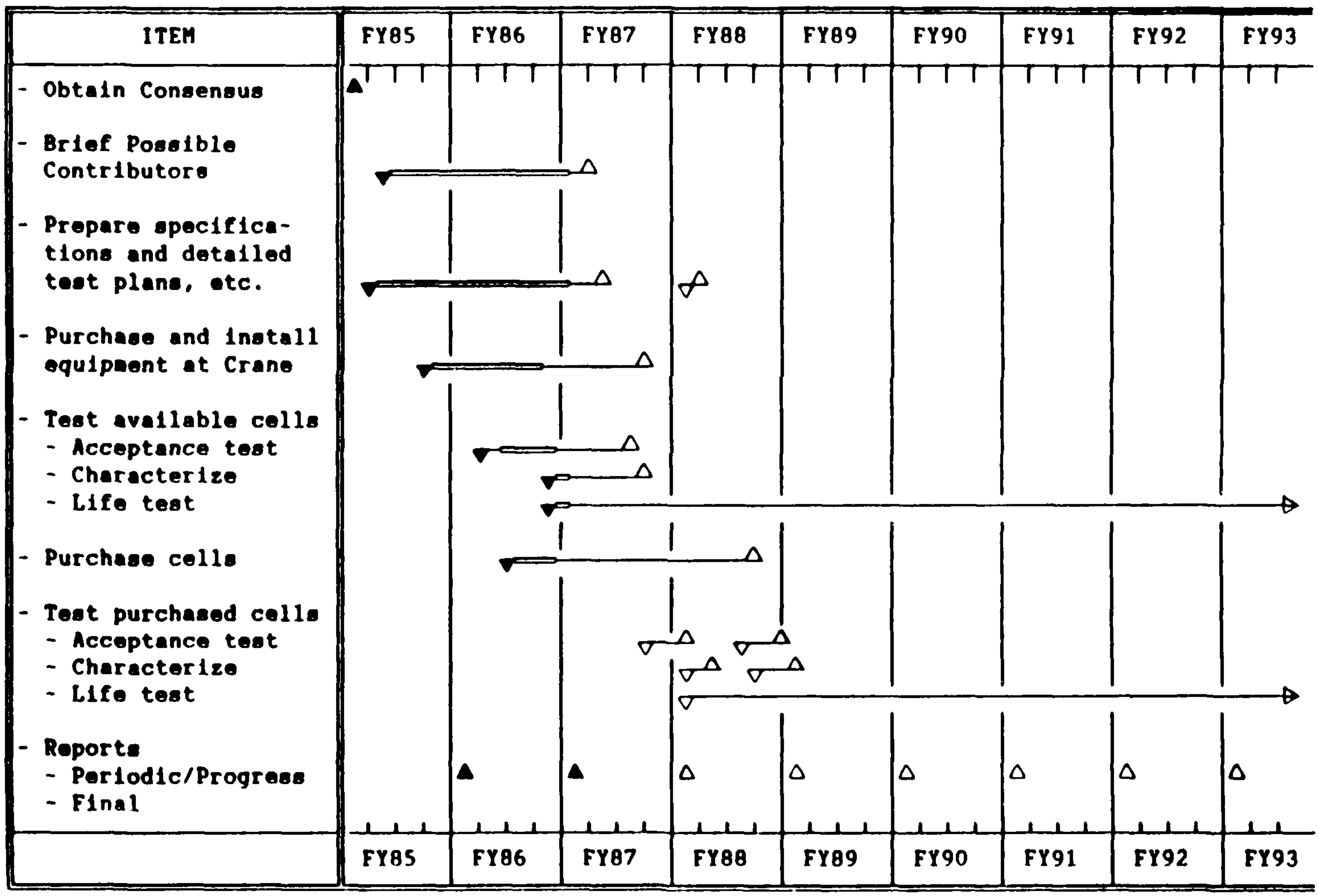

Figure 1. Schedule for the Nickel Hydrogen LEO Life Test Showing Testing Continuing Beyond 1993. The filled triangles indicate that the activity has begun, and the double line indicates the progress.

IV. STATUS

In Spring 1985, two Air Force System Program Offices (SPO's), AFWAL AeroPropulsion Laboratory (AFWAL/POOC), and the AFSTC completed a transition agreement that seeks to provide data needed to bring NiH_2 battery technology into general use in all intended applications. The two SPO's and the STC committed funds for the initiation of the testing. AFWAL/POOC agreed to provide NiH_2 cells from previous contracts for testing. The AFWAL Materials Laboratory agreed to commit the cells to the life test program. The numbers of 3.5 in. diameter cells committed to the test program and their expected availability dates are listed in Table 3.

Funding provided was sufficient to purchase test equipment, including a new computer facility for this test at NWSC Crane, and to proceed with the testing of the committed cells. This equipment will also serve as replacements for some of the outdated and less reliable equipment currently in use.

Test documentation including the life test plan, cell specification, and life testing procedure have been prepared and are currently undergoing review. Failure analysis documentation is yet to be prepared.

Cells have been received and are currently undergoing acceptance testing.

Additional funding is sought to complete the purchase of cells for the minimum test matrix shown in Table 2 and to assure the completion of the program.

Table 3. 3.5 in. Diameter NiH_2 Cells Committed to the Test

Source	Approximate Number[1]	Date Available
Yardney		
MANTECH	25 (ZA)	Winter 1986
AFWAL[2]	5 (ZA)	Winter 1986
Eagle Picher		
Adv. Dev. Prog.	24 (A)	Spring 1985
AFWAL	15 (Z)	Summer 1985
HAC[3] (for AFWAL)	18 (Z)	Spring 1985
GEBBD[4]		
AFWAL	15 (Z)	Winter 1986

[1]The letters indicate the type of separator: (A) asbestos, (Z) Zircar, and (ZA) MANTECH combination.

[2]Air Force Wright Aeronautical Laboratories.

[3]Hughes Aircraft Corporation.

[4]General Electric Battery Business Department.

V. SUMMARY

A program to demonstrate the long-term reliability of NiH_2 cells in LEO and support use in MAO has been initiated. Both 3.5 and 4.5 in. diameter NiH_2 cells are included in the test plan. Cells from all U.S. vendors are to be tested. The tests will be performed at -5 and 10°C at 40 and 60% DOD for LEO orbit and 10°C and 80% DOD for MAO orbit simulations. The goals of the testing are 20,000 cycles at 60% DOD and 30,000 cycles at 40% DOD. Cells are presently undergoing acceptance and characterization testing at NWSC Crane. Funding has been provided by the AFSTC and two AF SPO's to initiate the testing, but additional funding must be acquired to complete the purchase of cells and to assure completion of the testing.

LABORATORY OPERATIONS

The Aerospace Corporation functions as an "architect-engineer" for national security programs, specializing in advanced military space systems. Providing research support, the corporation's Laboratory Operations conducts experimental and theoretical investigations that focus on the application of scientific and technical advances to such systems. Vital to the success of these investigations is the technical staff's wide-ranging expertise and its ability to stay current with new developments. This expertise is enhanced by a research program aimed at dealing with the many problems associated with rapidly evolving space systems. Contributing their capabilities to the research effort are these individual laboratories:

Aerophysics Laboratory: Launch vehicle and reentry fluid mechanics, heat transfer and flight dynamics; chemical and electric propulsion, propellant chemistry, chemical dynamics, environmental chemistry, trace detection; spacecraft structural mechanics, contamination, thermal and structural control; high temperature thermomechanics, gas kinetics and radiation; cw and pulsed chemical and excimer laser development including chemical kinetics, spectroscopy, optical resonators, beam control, atmospheric propagation, laser effects and countermeasures.

Chemistry and Physics Laboratory: Atmospheric chemical reactions, atmospheric optics, light scattering, state-specific chemical reactions and radiative signatures of missile plumes, sensor out-of-field-of-view rejection, applied laser spectroscopy, laser chemistry, laser optoelectronics, solar cell physics, battery electrochemistry, space vacuum and radiation effects on materials, lubrication and surface phenomena, thermionic emission, photosensitive materials and detectors, atomic frequency standards, and environmental chemistry.

Computer Science Laboratory: Program verification, program translation, performance-sensitive system design, distributed architectures for spaceborne computers, fault-tolerant computer systems, artificial intelligence, microelectronics applications, communication protocols, and computer security.

Electronics Research Laboratory: Microelectronics, solid-state device physics, compound semiconductors, radiation hardening; electro-optics, quantum electronics, solid-state lasers, optical propagation and communications; microwave semiconductor devices, microwave/millimeter wave measurements, diagnostics and radiometry, microwave/millimeter wave thermionic devices; atomic time and frequency standards; antennas, rf systems, electromagnetic propagation phenomena, space communication systems.

Materials Sciences Laboratory: Development of new materials: metals, alloys, ceramics, polymers and their composites, and new forms of carbon; nondestructive evaluation, component failure analysis and reliability; fracture mechanics and stress corrosion; analysis and evaluation of materials at cryogenic and elevated temperatures as well as in space and enemy-induced environments.

Space Sciences Laboratory: Magnetospheric, auroral and cosmic ray physics, wave-particle interactions, magnetospheric plasma waves; atmospheric and ionospheric physics, density and composition of the upper atmosphere, remote sensing using atmospheric radiation, solar physics, infrared astronomy, infrared signature analysis; effects of solar activity, magnetic storms and nuclear explosions on the earth's atmosphere, ionosphere and magnetosphere; effects of electromagnetic and particulate radiations on space systems; space instrumentation.

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